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Influence of transverse rebar on shear behavior of Y-type perfobond rib shear connection

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HIGHLIGHTS

- Behavior of Y-type perfobond rib shear connections with various strength and diameter of transverse rebar were evaluated.
- Push-out tests were conducted to evaluate the shear resistance and ductility of Y-type perfobond rib shear connections.
- Push-out test results were compared with predicted results by existing models.
- Failure modes of Y-type perfobond rib shear connections were classified into three types.

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ABSTRACT

This study experimentally investigated the effects of transverse rebar on the shear behavior of Y-type perfobond rib shear connectors. Push-out tests were performed on 12 specimens for which the strength and diameter of transverse rebar were utilized as variables. Test results from a previous study were used to confirm the shear strength and ductility of the Y-type perfobond rib shear connectors, along with the initial cracking and failure modes of the concrete. The results showed that shear strength increased as the diameter of the transverse rebar increased, and this effect was amplified in concrete with lower compressive strength.

1. Introduction

There have been various applications of steel-concrete composite structures that utilize shear connectors in the construction industry. Steel-concrete composite systems that utilize headed studs are typically used, and various types of shear connectors are used depending on the purpose of the shear connection. Shear connectors are embedded between a concrete slab and a steel beam to form a shear connection, which allows for the transfer of shear force between the two materials; this activity creates a composite effect. The most commonly used shear connector is the headed stud, and studies on it started back in 1920s. Official studies started when Caughey stated the need for shear connectors that could resist horizontal shear forces [1]. Viest proposed the shear resistance equation by conducting load tests on stud shear connections [2]. Later, studies considering different variables such as concrete material properties, cross-section, height, and the tensile strength of studs were conducted [3–5]. Recently, large stud shear connectors with diameters larger than 22 mm were studied to increase shear resistance capacity [6–8].

To achieve high shear strength using existing stud shear connectors, a large number of shear connectors are required, which increases the amount of work and cost. Furthermore, there is a risk of shear connection failure due to fatigue. In 1987, Germany developed perfobond rib shear connectors that increased shear resistance and solved the fatigue problem associated with stud shear connectors [9]. Vianna et al. conducted an experimental study on beams that had T-type shear connectors [10] and compared the structural behavior of perfobond rib shear connectors and T-type shear connectors [11]. Recently, in Europe, composite dowel-type shear connectors were developed for composite girders [12,13]. The Y-type perfobond rib shear connectors developed by Kim et al. in 2013 were shear connectors that improved the inconvenience of reinforcing work with transverse rebar in previous perfobond rib shear connectors [14]. Moreover, various tests were conducted to predict shear strength [15,16]. In addition, the per-

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fobond rib shear connectors showed excellent fatigue performance and energy dissipation capability for fatigue loads and low-cycle fatigue loads that occurred from design truck loads on highway bridges [17,18].

Various types of shear connectors were developed based on the type of shear connection performance required by composite structures. The material properties and design dimensions of shear connectors, concrete, and reinforcements affect the performance of shear connections, which consist of steel, concrete, reinforcement rebar, and shear connectors. The shear strength and ductility of Y-type perfobond ribs, flat-type perfobond ribs, and composite dowel shear connectors are particularly affected by transverse rebar in a significant manner. Kim et al. conducted push-out tests on Y-type perfobond rib shear connectors without transverse rebar and with transverse rebars with deformed bar diameters of 13 mm, 16 mm, and 19 mm [14,19]. The shear structural performance of the Y-type perfobond rib shear connector was analyzed according to variables such as the Y-rib shape and thickness, concrete compressive strength, presence or absence of transverse rebar, and flat-type perfobond rib shear connectors. Based on test results, an equation for predicting shear resistance was proposed [14]. In order to improve this shear resistance equation, additional push-out tests were performed considering different conditions such as the ratio of rib width-to-height and number of ribs. A numerical model was also proposed, and a parametric study was performed for various conditions. Finally, an improved shear resistance equation was suggested based on the experimental and parametric data [19]. However, there is still a lack of analysis of the structural behavior caused by the difference of steel grades and diameter of the transverse rebar, since various types of transverse rebar can be applied in situ. The differences in steel types such as diameter or steel grade, can affect the shear connection; hence, there is a need for performing an analysis of the effects of transverse rebar steel type. Filling this knowledge gap is the aim of this study.

Recently, reinforcements have begun to utilize high-strength materials with varying diameters (as opposed to a single diameter) for effective cross-section composition in composite structures. Moreover, many studies on the effects of transverse rebar on shear connections are being performed. These studies were mainly focused on the performance differences observed when transverse rebars were present or absent. Nishido et al. experimentally confirmed that perfobond rib shear connectors with transverse rebars showed slightly better shear performance [20]. Kim et al. analyzed the effects of transverse rebars in composite dowels [21]. Studies on the diameter and strength of transverse rebars are in progress. Nakajima et al. analyzed the effects of the diameters of transverse rebars on perfobond rib shear connectors [22]. Zhang et al. studied the effects of transverse rebars on collective perfobond rib shear connectors installed in quantities [23]. He et al. studied the effects of the diameter of dowel holes, and the strength and presence of transverse rebars on shear resistance [24].

Currently available studies on the effects of transverse rebar on shear connections are concentrated on perfobond ribs; thus, additional studies that consider other various conditions are required. Flat-type perfobond rib shear connectors, composite dowels, and Y-type perfobond rib shear connectors each have their own advantages and shear behavior characteristics; therefore, studies on different types of shear connections should be performed. In particular, studies that focus on the effects of transverse rebars on Y-type perfobond rib shear connectors have not been performed. Thus, this study experimentally confirmed the shear behavior of Y-type perfobond rib shear connectors based on the strength and diameter of transverse rebar through push-out tests. The shear behavior obtained for each type of transverse rebar showed a difference of 10% and 13% in yield strength and tensile strength for SD400 and SD500, respectively. In addition, the yield strengths obtained using SD500 transverse rebars with diameters of 16 mm, 19 mm, and 22 mm (D16, D19, D22) were studied and compared. Aside from shear behavior, crack formation and distribution, and failure modes were also analyzed.

2. Push-out tests on Y-type perfobond rib shear connectors with various transverse rebars

2.1. Test specimens

The direct shear specimen standard suggested by Eurocode-4 [25] was used as reference to manufacture the push-out test specimens. The ribs of the Y-type perfobond rib shear connectors were bent in order to resist against the vertical separation of steel-concrete structures. Dowel holes were present between the ribs for installing the transverse rebar [14,17]. The Y-ribs used in the push-out test had an angle of 60° between each rib, a rib height of 100 mm, a width of 80 mm, a thickness of 10 mm, and a hole diameter of 40 mm. The Y-ribs were welded to a 24 mm-thick steel plate and a transverse rebar was reinforced between each dowel hole. To eliminate end-bearing effects in the Y-type perfobond rib shear connector, 70 mm of Styrofoam was attached to each end of the ribs. Grease was applied before casting concrete to prevent chemical bonding between the steel and concrete. Detailed specifications of the specimens are shown in Fig. 1.

Concrete with a design compressive strength of 50 MPa (C50) and ribs made of structural steel (SS400) were used to manufacture the specimens. SS400 steel is required to have a tensile strength of 400 MPa or higher, according to Korean Highway Bridge Specifications [26]. The specimens manufactured to confirm the effects of transverse rebar were manufactured to have diameter and strength as variables. The specimens for which diameter was utilized as the variable used SD500 rebar, which is required to have a yield strength of 500 MPa or higher [26], and it was used with three different diameters: 16 mm (D16), 19 mm (D19), and 22 mm (D22). The specimens with strength as the variable used SD 400 rebar [26], which is required to have a yield strength of 400 MPa or higher, and featured a diameter of 16 mm (D16). The material properties of concrete and structural steel are listed in Table 1. The name of each specimen and the variables of the transverse rebar are listed in Table 2. Three specimens were manufactured for each set of specifications, which created 12 specimens in total for the push-out test.

2.2. Test procedure

The push-out test for the Y-type perfobond rib shear connectors was conducted using a universal testing machine (UTM) with a capacity of 5000 kN. The loading rate was set to 0.04 mm/s, based on the test method in Eurocode-4 [25], which prevents the push-out test specimen from failing within the first 15 min. The load magnitude acting on the specimen was measured using a load cell installed on the UTM. Furthermore, to measure the relative slip between the steel and concrete that occurs in the mid-section of the Y-type perfobond rib, four linear variable differential transformers (LVDTs) were installed. The load-relative slip curve obtained from the UTM and LVDTs were used to evaluate the shear strength and ductility of the specimen.

A strain rate gauge was attached to the transverse rebar to measure the strain rate of the rebar that occurs from the relative slip of the specimen. If too many strain rate gauges are attached, the contact area between steel and concrete could decrease due to grinding work and adhesives, which lowers bond strength. Therefore, the attachment of strain rate gauges was planned within a range that was determined to not affect the shear behavior. Strain rate